Global and Planetary Change 176 (2019) 50–59

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Geomorphic control on regional glacier lake outburst flood and debris flow activity over northern Tien Shan

V. Zaginaev[a,*], D. Petrakov[b], S. Erokhin[a], A. Meleshko[a], M. Stoffel[c,d,e], J.A. Ballesteros-Cánovas[c,d]

[a] Institute of Water Problems and Hydro-energy, National Academy of Science, Bishkek, Kyrgyzstan
[b] Faculty of Geography, Lomonosov Moscow State University, Moscow, Russia
[c] Dendrolab.ch, Department of Earth and Environmental Sciences, University of Geneva, 1205 Geneva, Switzerland
[d] Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, 1227 Carouge, Switzerland
[e] Department F.-A. Forel for Aquatic and Environmental Sciences, University of Geneva, 1205 Geneva, Switzerland

ARTICLE INFO

Keywords:
GLOF
Debris flow
Cryosphere
Tree rings
Dendrogeomorphology
Tien Shan
Kyrgyzstan

ABSTRACT

Glacier lake outburst floods (GLOFs) and related debris flows (DF) are significant natural threats in the Tien Shan Mountains. Their occurrence is favoured by the formation of new glacier lakes and the destabilization of moraines and hillslopes due to climate warming. Understanding the frequency-magnitude of these processes is essential for the implementation of Disaster Risk Reduction strategies. Yet, long-term records of past GLOFs or DF in the region are almost completely missing, which renders rational hazard and risk assessments difficult. Here, we present a unique, multi-century dataset of regional GLOF-DF reconstruction for the Tien Shan based on tree-ring analyses from six different torrential fans, and provide insights on regional processes activity. Based on this dataset, we also test whether GLOF-DF activity is related to glacier degradation and changes in geomorphic characteristics at the catchment scale. Results from > 430 disturbed trees growing on six different DF fans suggest frequent GLOF-DF activity since the 19th century, which is consistent with available historical records. We also observe an increase in process activity during the mid-20th century coinciding with phases of glacier stagnation or even slight glacier advances. This means GLOF-DF activity in northern Tien Shan is inversely related to moraine-glacier ratios as well as to glacier area shrinkage rates and fan characteristics (such as slope and depositional area). These findings imply that glaciological and geomorphic features could be used for regional susceptibility assessments in the future. Results presented here are the longest, annually resolved GLOF-DF series in the region, if not worldwide, and constitute a unique dataset to understand process variability. As such, they should be used for further climate change adaptation to mitigate natural hazard and risk in the region.

1. Introduction

Climatic warming has a noteworthy impact on the cryosphere in high mountain regions, thereby affecting the frequency and magnitude of geomorphic processes such as glacial lake outburst floods (GLOFs), debris flows (DF), landslides, or snow avalanches [Stoffel et al., 2014; Beniston et al., 2018; Ballesteros-Cánovas et al., 2018]. In Central Asia, rapid observed [Hu et al., 2014] and predicted [Hawkins and Sutton, 2016] regional warming has led to severe changes at high altitudes including intense permafrost degradation and glacier downwasting [Marchenko et al., 2007; Aizen et al., 2006; Farinotti et al., 2015; Petrakov et al., 2016]. This process has been particularly quick in Western and Northern Tien Shan when compared to the Inner and Central Tien Shan ranges [Sorg et al., 2012], resulting in intense geomorphic changes, the formation of new glacial lakes [Wang et al., 2015] and an expansion of some of the existing lakes [Engel et al., 2012]. These changes in river runoff, GLOFs and glacier related debris flows have significant social and economic consequences in lower-elevation valleys and even in adjacent lowlands [Sorg et al., 2014].

One may also wonder whether and how these changes in the cryosphere will affect the frequency and magnitude of extreme rainfall- or lake outburst-induced debris flows (GLOF-DF) in the future. In the absence of information on these changes, predictions remain challenging and may likely jeopardize the implementation of any adaptation strategy aimed to improve the resilience of mountain inhabitants [Ballesteros-Cánovas et al., 2017; Moss et al., 2010]. Specifically in the Northern Tien Shan region, GLOFs and DF pose a threat to numerous settlements, including some of the major cities and towns [Narama et al., 2018], and several disasters have occurred in the region over the past decades. For instance, a large DF occurred in 1921, causing

* Corresponding author at: Institute of Water Problems and Hydro-energy, 533 Frunze Street, Bishkek 720033, Kyrgyzstan.
E-mail address: zagivitjob@gmail.com (V. Zaginaev).

https://doi.org/10.1016/j.gloplacha.2019.03.003
Received 29 November 2018; Received in revised form 20 February 2019; Accepted 4 March 2019
Available online 05 March 2019
0921-8181/ © 2019 Elsevier B.V. All rights reserved.

multiple casualties in Almaty [Vinogradov, 1980]. Similarly, the city of Bishkek (Kyrgyzstan) was affected by a GLOF event in 1953 [Erokhin et al., 2018]. More recently, a catastrophic transboundary GLOF event occurred in Shakhimardan River (Kyrgyzstan/Uzbekistan), claiming > 100 victims in 1998 [Usubaliev and Erokhin, 2007]. Likewise, extreme events were recorded at Zyndan Glacier, Issyk-Kul region in 2008 [Narama et al., 2010] and in the Adygene Valley in 2012 [Erokhin et al., 2018], affecting the city of Bishkek. According to the Kyrgyz Ministry of Emergency, > 1200 debris flows and floods have been recorded on the national territory of Kyrgyzstan since 2000.

Most GLOF-DF events recorded in Kyrgyzstan have been linked to the degradation of moraine-glacier complexes [Usubaliev and Erokhin, 2007; Jansky et al., 2010] including glaciers, unconsolidated debris-covered areas, rock glaciers, lateral and terminal moraines. According to these authors, the thawing of the terminal moraines would have induced and increased subsurface flow, which in turn may have resulted in piping and erosive processes of terminal moraines, and consequently in a destabilization of the fragmented material [Benn and Owen, 2002]. The varying morphology of these moraine-glacier complexes can be interpreted as a function of the complex interplay between the erosional energy and debris supply [Gomez and Small, 1985]. Debris is transported by glaciers and accumulated in areas where glacier flow velocity is decreased down to zero to form large and steep lateral and terminal moraines that are continuously modified by meltwater erosion and slope failures [Benn and Owen, 2002].

Based on the work described above, we use moraine-glacier complex morphology to describe GLOF-DF activity with the aim of improving our capacity to perform sustainable hazard and risk assessments in the region. Yet, the lack of long-term, regional-scale reconstructions of GLOF-DF activity has prevented assessments based on moraine-glacier complex indicators so far.

Therefore, in this paper, we show how an improved understanding of GLOF-DF activity at the regional scale provides valuable baseline information to perform contrasting analyses aimed at identifying geomorphic indicators for regional hazard assessments. Here, we combine tree-ring analyses, aerial- and satellite imagery interpretation and historical archives to build an unprecedented, regional, annually-resolved history of GLOF-DF processes for selected catchments in the northern Tien Shan region. The dating of growth -ring anomalies in old-growth trees growing on fans [Stoffel and Corona, 2014] has been proven previously to be a valuable tool for GLOF-DF reconstructions in the region [Zaginaev et al., 2016]. In addition, the approach has been widely used elsewhere to unravel spatio-temporal variations of hydro-geomorphic process activity [Stoffel, 2010; Ballesteros-Cánovas et al., 2017], to determine meteorological triggers [Schneuwly-Bollschweiler and Stoffel, 2012; Stoffel et al., 2014; Ballesteros-Cánovas et al., 2018] and to perform hazard and risk assessment [Bollschweiler et al., 2008; Allen et al., 2018].

The specific aims of this paper therefore are: (i) to provide a regional reconstruction of DF activity in northern Tien Shan; and (ii) to test whether differences in moraine-glacier complex indictors can explain dissimilar DF activity.

2. Study site

The study site comprises two neighboring glacierized catchments located in the Ala-Archa (74°24′ E–74°34′ E; 42°25′ N–42°42′ N) and Alamedin valleys (74°34′ E–74°44′ E; 42°25′ N–42°42′ N). All sites are located along the Kyrgyz Ridge in the northern Tien Shan region, 40 km south from Bishkek (Fig. 1A). The valleys have comparable areas, with catchment sizes of almost 270 km^2 in the case of Ala-Archa valley and 317 km^2 for Alamedin Valley. Altitudes in both cases range from 1400 to 4890 m asl. These valleys are the results of tectonic activity, with the existence of pre-Paleozoic metamorphic and Lower Paleozoic islands of sedimentary-volcanogenic formations [Erochin et al., 2009]. Glacial cover in the Ala-Archa Valley is currently 33.3 km^2 [Bolch, 2015]; whereas in the Alamedin Valley they cover 45.7 km^2 [Meleshko et al., 2017]. The existence of glacier lakes prone to trigger GLOFs is higher in the Ala-Archa Valley as compared to the Alamedin Valley. Currently, in the Ala Archa Valley, two glacier lakes exist at the termini of the Adygene and Teztor glaciers, and one lake formed by the retreating Uchitel Glacier. In the Alamedin Valley, a rockfall-dammed lake has been reported by Erokhin and Dikih [2003]. Six debris fan have been selected for the GLOF-DF reconstruction. All fans are partially covered with *Picea abies* and *Juniperus pseudosabina* on the older deposits and with *Betula turkestanica* on the younger deposits. Four of these DF fans are located in the Ala-Archa Valley and named Adygene (AD), Aksay (AK), Teketor (TE), Topkaragay (TO) and; two DF fans are found in the Alamedin valley and known as Salyk (SA) and Kuturgansuu (KU) (Fig. 1B, C). All fans present evidence of recent DF activity. The six catchments range in size from 5.2 km^2 (TE) to 37.9 km^2 (AD). Table 1 provides specific physical characteristics of each catchment, based on the interpretation of multi-temporal aerial and satellite imagery, field surveys and hydrometric measurements. The mean annual modulus of flow (M), estimated as a ratio between mean annual water discharge (Q, l/s) and catchment area (F, km^2),

$$M = Q/F \quad (1)$$

ranged from 8.2 (TE) to 36.1 (KU) l/(s × km^2). The Melton's ruggedness index, defined as the difference between the maximum and minimum elevation in the catchment (Δh) divided by the square root of the catchment size

$$Me = \Delta h/\sqrt{F} \quad (2)$$

[Melton, 1965] shows values ranging from - 0,58 (SA) and 0,20 (KU).

The ratio between moraine (M) and glacier (G) covered area is also presented in Table 1. We hypothesize that this ratio is an important factor reflecting moraine formation activity under conditions of glacier degradation. The moraine covered area (M) includes both debris-covered parts of glaciers and terminal moraine areas as well as the rock glaciers, hummocky terrains and ice-rich glacial till deposits located below the glacier snout. The glacier (G) covered area includes clean ice and snow, i.e. part of a glacier without debris cover. In 1960, the M/G ratio for the six catchments were 0.30 on average, with somewhat higher values for AD (0.38) and lower values for KU (0.20). Today, the average M/G ratio is 0.49, with the highest value in the case of TE (0.68) and the lowest values at KU and AD (0.34). These values reflect the dissimilar evolution of glaciers in the catchments over the last decades (see Table 1).

3. Material and methods

3.1. Geomorphic description and tree sampling

The geomorphic and forest cover description of the investigated catchments was based on the interpretation of available aerial and satellite imagery from the years 1960, 1971, 1978, and 2015, 2016, as well as on field surveys. Longitudinal slope (gradient) of the channel bed (m m^{-1}) for fans was calculated as a change in elevation divided by the length of the fan, using ArcGIS 10.3® on all previously georeferenced aerial and satellite images. Geomorphic features such as lobes, levees, or channels were manually digitalized at the fan level, whereas debris cover and the existence of lakes were digitized at the glacier level. This procedure was chosen as human interpretation remains the best tool for extracting detailed information from satellite imagery for glaciers [Raup et al., 2007], thus we manually delineated all boundaries using the approach described by Petrakov et al. (2016). A 10 m spatial resolution DEM generated from Sentinel-1 image in SNAP® software was used to determine catchment areas, as well as other geomorphic descriptive characteristic showed in the Table 1 and Table 2.

During field survey, trees growing in exposed positions along the channels, lobes, and other depositional features of the fan were

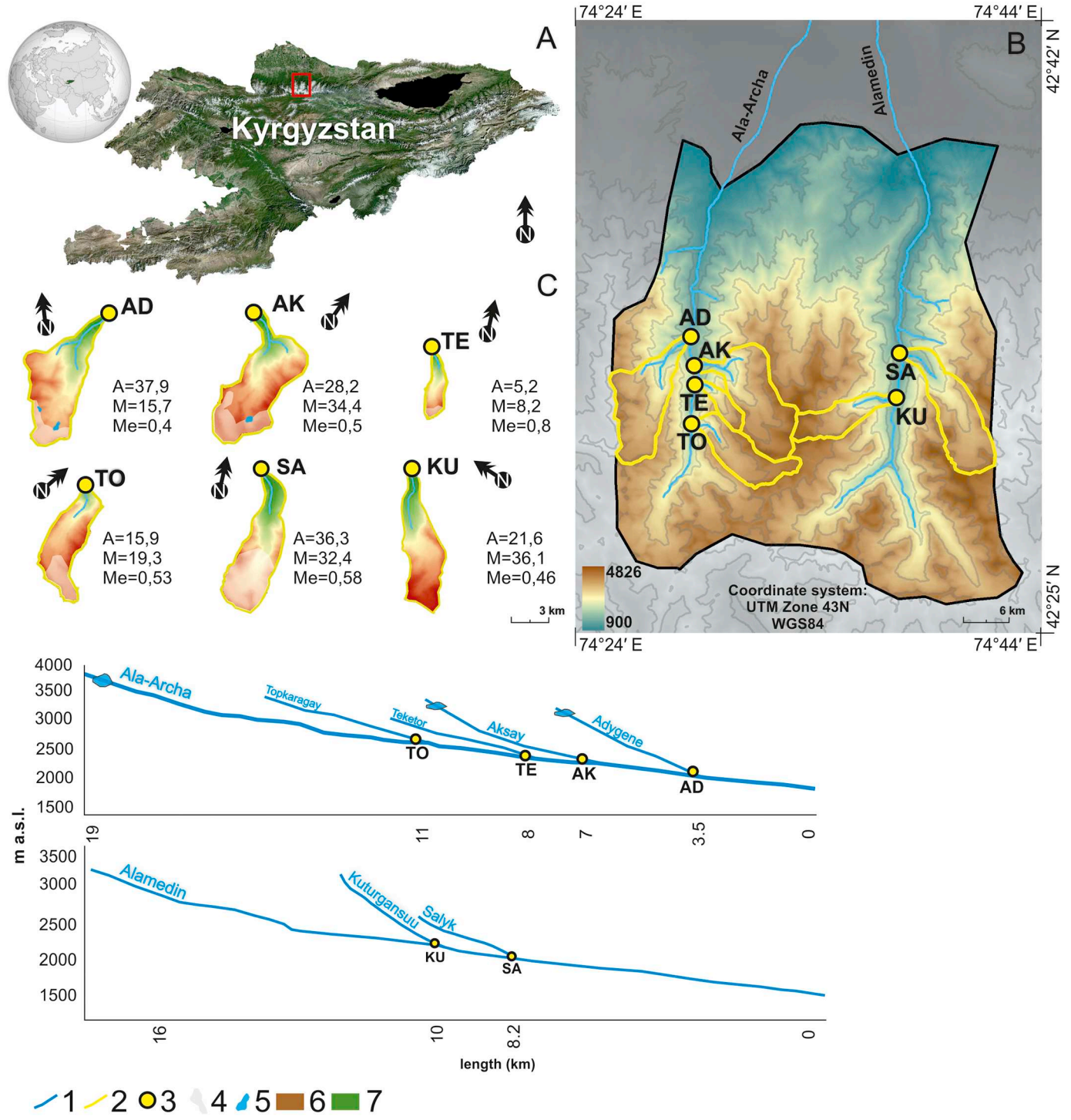

Fig. 1. Location and main characteristics of the six study sites. A) The red square indicates the general location of the study region in the northern part of Kyrgyzstan, (B) The Ala-Archa and Alamedin valleys have a south-north orientation, C) Main characteristics and longitudinal profiles of each sub-catchment: AD- Adygene, AK – Aksay, TE – Teketor, TO – Topkaragay in Ala-Archa Valley; SA – Salyk; KU – Kuturgansuu in Alamedin Valley. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

screened for evidence of past DF events such as scars on stems, stem tilting or exposed roots [Stoffel and Bollschweiler, 2008]. Sampling of trees was performed using increment borers and eventually handsaw. At least two increment cores were taken per tree according to Stoffel and Corona [2014]. Eventually, we also obtained wedges or cross-sections from smaller trees and exposed roots, respectively [Ballesteros-Cánovas et al., 2010a, 2010b, 2017; Stoffel et al., 2012; Bodoque, 2015]. The sampling was conducted according to the flow direction of events, and at stem heights between 20 and 100 cm form the ground. In all cases, sampled trees were restricted to areas without evidence of

Table 1
Key parameters of the analyzed catchments and their DF fans. *G* defines the glacier area, while *M* defines the moraine complex area.

Valley	Catchment, km^2	Modulus of flow annual, l/(s × km^2)	Melton Index	G (1960), km^2	G (2017), km^2	M (1960), km^2	M (2017), km^2	M/G (1960)	M/G (2017)
AD	37.9	15.7	0.38	5.4	4.4	2.1	2.5	0.38	0.56
AK	28.2	34.4	0.5	7.0	5.8	1.5	2.0	0.21	0.34
TE	5.2	8.2	0.87	0.52	0.37	0.2	0.31	0.33	0.68
TO	15.9	19.3	0.53	4.3	3.25	1.6	1.8	0.37	0.55
SA	36.3	32.4	0.58	9.5	7.2	2.8	3.5	0.32	0.47
KU	21.6	36.1	0.46	3.9	3.2	0.8	1.1	0.20	0.34

Table 2
Debris-flow (DF) depositional characteristics on the six fans investigated based on information from historical aerial and recent satellite images.

Fan	Year	Depositional area (km^2)	Forest area (km^2)	Maximum length of deposits from cone apex (m)	Channel width in upper fan area (m)	Slope from source to fan apex, ‰	Slope on DF fan‰
AD	1960	0.08	0.03	650	35	201	138
	1978	0.07	0.05	670	25	190	149
	1988	0.03	0.05	684	25	210	130
	2015	0.04	0.05	680	22	194	145
AK	1960	0.16	0.34	640	22	270	120
	1971	0.21	0.28	575	35	265	138
	1978	0.19	0.29	551	35	261	131
	2015	0.11	0.46	525	26	256	111
TO	1962	0.03	0.01	377	12	284	286
	1988	0.02	0.01	360	14	275	295
	2015	0.02	0.01	350	15	290	301
TE	1960	0.01	0.02	345	27	290	247
	1988	0.01	0.03	343	23	280	251
	2015	0.01	0.03	302	25	297	240
SA	1960	0.01	0.1	740	10	120	250
	1988	0.01	0.12	740	10	120	247
	2016	0.01	0.06	743	11	115	260
KU	1962	0.16	0.48	1050	62	300	203
	1988	0.14	0.5	990	58	300	197
	2015	0.12	0.56	980	51	310	200

human influence (i.e., tourist facilities, road, paths, and other infrastructure). We also took samples from undisturbed trees (growing next to the fans) to build a reference chronology with the purpose of dating and detecting growth anomalies of disturbed trees.

3.2. Detecting DF signal in tree-ring records

In the laboratory, all samples were prepared and measured according to the approach proposed by Stoffel and Corona (2014). First, tree rings were counted and then measured using a digital LINTAB positioning table connected to a Leica stereomicroscope and the TSAPW in software [Rinntech, 2011] with a precision of 0.01 mm. Tree-ring widths from undisturbed trees were measured as well and converted into width indices by standardizing raw data. Pointer years were used for visual cross-dating of disturbed tree-ring series [Stoffel and Bollschweiler, 2008]. Afterwards, we focused on the detection of growth disturbance (GD) induced by past DF activity. GD were divided into three different classes according the intensity and type of reaction [Stoffel and Corona, 2014]: (i) strong reactions (i.e., injuries, intense tangential rows of traumatic resin ducts, or TRDs); (ii) medium reactions (i.e., callus tissues, compression wood, or intense abrupt growth changes); and (iii) weak reactions (i.e. moderate growth increases and/or growth suppressions). Whenever possible, TRD were used to define the seasonality of events [Stoffel, 2008; Stoffel and Hitz, 2008; Bollschweiler et al., 2008]. The definition of past debris flow event at the catchment level was based on the weighted index value (Wit) as defined by Kogelnig-Mayer et al. (2011) as well as the number of GD (Eq.3).

$$W_{it} = \left(\left(\sum_{i=1}^{n} T_i \times 7 + \sum_{i=1}^{n} T_s \times 5 + \sum_{i=1}^{n} T_m \times 3 + \sum_{i=1}^{n} T_w\right)\right) \times \frac{\sum_{i=1}^{n} R_t}{\sum_{i=1}^{n} A_t} \quad (3)$$

This index accounts for the quantity and intensity of growth disturbances (GDs) at each year, and the number of trees available for the reconstruction. We defined thresholds for the event identification based on previous work realized in the region [Zaginaev et al., 2016]. Moreover, visual analyses based on the spatial distribution of the affected trees in the fan was also performed in order to detect potential incongruences (affected trees concentrated in a small area or highly disperse without defining a channel pattern) on the location of the disturbed trees [Lopez-Saez et al., 2012; Schneuwly et al., 2013]. Specifically, we use $W_{it} > 1{,}2$ for certain events; $1{,}2 > W_{it} > 0{,}8$ for potential events; and $W_{it} < 0{,}8$ to classify reactions as noise.

3.3. Estimation of the moraine-glacier complexes

We used morphological variability of moraine-glacier complexes as explanatory variable to explain dissimilar GLOF-DF catchment activity. Morphological variability of the complexes can be interpreted as a function of the complex interplay between the erosional energy and debris supply (and accumulation of material farther downstream) [Wu, 1992]. In fact, moraine complexes can to suppress DF activity because of the limited flow capacity of meltwater in internal drainage channels [Zaginaev, 2013]. To analyse these observations, we defined a moraine-glacier complex index, expressed by the ratio between the moraine complex area, including area of glacier cover by debris plus area of ice-rich deposits below a glacier (M; in terms of discrete debris accumulation) and the debris-free part of a glacier (G; able to produce and transport meltwater). We test whether this index is related in any way to the GLOF-DF activity as reconstructed from tree-ring records. To this end, we performed an intra-catchment comparison to test data for correlations between the M/G ratio and derived geomorphic parameters as explanatory variables, and the GLOF-DF activity of each catchment as explained variable.

4. Results

4.1. Geomorphic changes related to GLOF-DF activity

Fig. 2 shows the evolution of the active depositional and Table 2 shows forested areas based on existing aerial (scale of survey 1:36000) and satellite images (Sentinel-2, a spatial resolution 10 m) on all fans for each available year. On the AD fan, large, fresh deposits could be observed on the oldest imagery dating back to the early 1960s. Thereafter, forested surfaces increased until 2012, when a DF event on July 31, 2012 deposited large amounts of material in the central part of the fan. At AD, channel width decreased from 35 m in 1960 to 22 m in 2015 in the upper part of the fan. By contrast, slope angles on the DF fans showed high values in 1978 and 2015 (Table 2). In the Ala-Archa Valley, the AK fan presented the most noteworthy geomorphic changes. In 1960, several depositional features are recognized along different channels reaching the lower part of the fan. During the 1970s, large amounts of DF material reached the main Ala-Archa Valley, thereby affecting the existing forest in the central part of the fan, and resulting

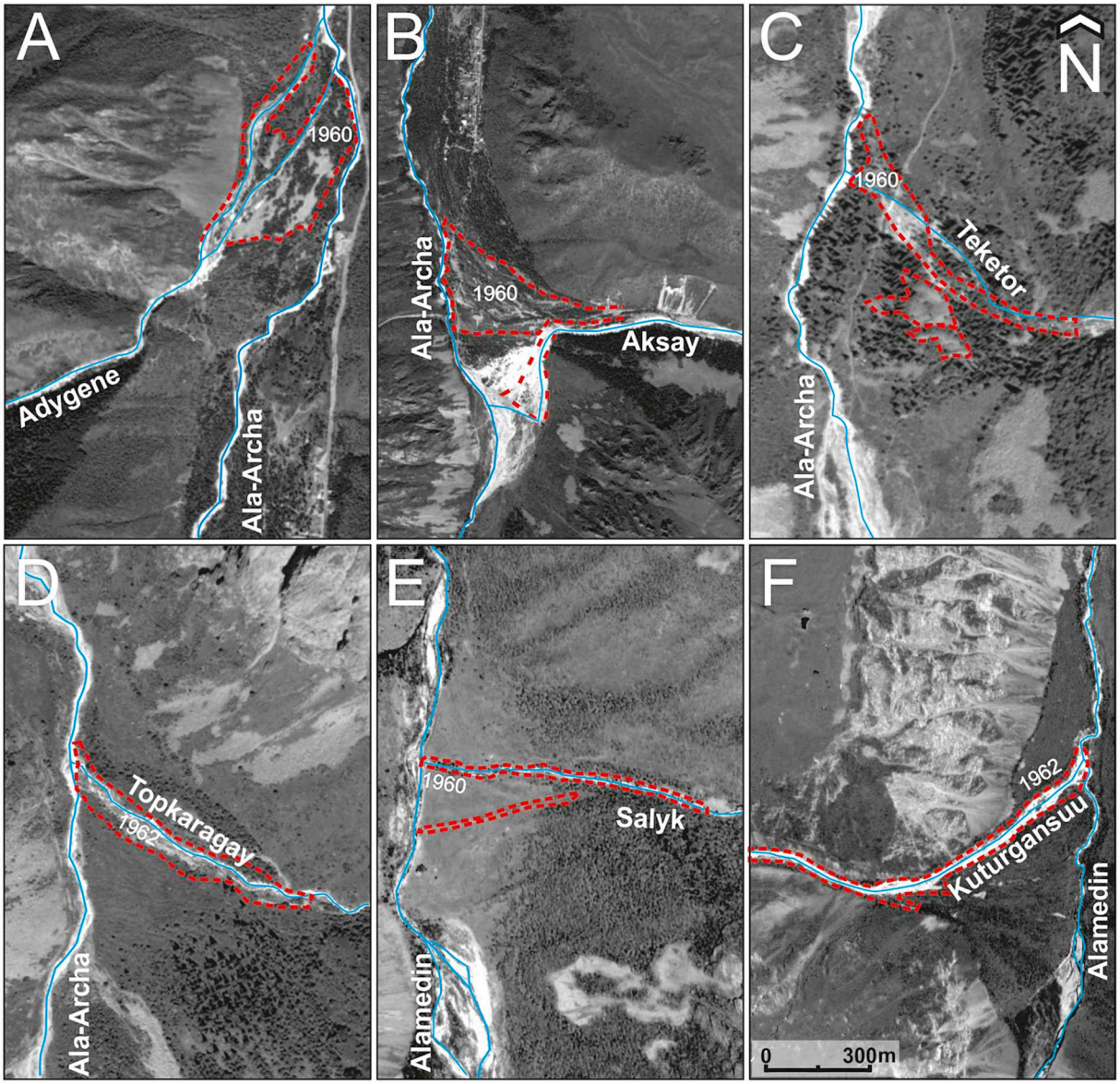

Fig. 2. A. Adygene fan (2017) with deposits on the 1960 photo (dotted line). B. Aksay fan (2016) with deposits as seen on the 1960 aerial imagery (dotted line). C. Teketor fan (2015) with deposits on the 1960 imagery (dotted line) D. Topkaragay fan (2015) with deposits visible on the 1962 image (dotted line) E. Salyk fan (2015) with deposits visible on the 1960 aerial picture (dotted line). F. Kuturgansuu fan (2016) with deposits as seen in 1962 (dotted line).

Table 3
GLOF-DF chronologies for the Ala-Archa and Alamedin valleys as derived from tree-ring records and historical archives (the latter are marked with a *, source: Kyrgyz complex hydrogeological expedition).

Valley	Site	Year of event	Number of events
Ala-Archa	AD	1910; 1934, 1953*, 1966, 1980, 1982; 1988*, 1993, 2012*	9
	AK	1877, 1885, 1916, 1918, 1922, 1924, 1928, 1934, 1936, 1941, 1943, 1950, 1955, 1960*, 1961*, 1965*, 1966*, 1968*, 1969*, 1970*, 1973, 1975, 1977, 1980*, 1993, 1999*, 2015*	27
	TO	1928, 1953, 1968, 1974*, 1988, 1993*	6
	TE	1900, 1946, 1953, 1958, 1959, 1968, 1978, 1980, 2003	9
Alamedin	SA	1938, 1956, 1961, 1970, 1975, 1980	6
	KU	1846, 1882, 1902, 1904, 1928, 1956, 1958, 1966,1980, 1982, 1984, 1988, 1993, 1999, 2000, 2003, 2010	17

in a reduction of the forested area by almost 18%. During this time, the main channel in the upper part of the fan was wider (up to 35 m), and the slope of the DF fan increased by 15% as compared to the situation in the 1960s. From 1978 to 2015, the forest has almost recovered on the fan. During this period, the surface and length of the active depositional zone as well as the width and the slope of the channel have been reduced on the debris flow fan (Table 2). At fan TE, the depositional area has remained fairly stable between 1960 and 1988, although the forested area has increased slightly. The aerial image from 1978 shows a reactivation of a central flow path. Between 1988 and 2015, the depositional area decreased, this process was accompanied by an increase of the forested area. During this same time window, we detect a slight

slope increase on the fan. On TO fan, the most relevant geomorphic changes occurred prior to 1960. The geomorphic assessment suggests that DF events that occurred during the period covered by imagery were not powerful enough to modify the structure of the fan. As a result, the depositional area has decreased between 1962 and 2015, whereas forest cover has increased accordingly. At the same time, however, channel width and slope has increased during the same period, probably as a result of debris-flow activity (Table 3) and erosion on the fan.

In the Alamedin Valley, no relevant geomorphic changes could be identified on the SA fan over the studied period, and therefore, the depositional area, channel length, and channel width did not vary.Both the depositional area and channel width decreased at KU over the period covered by imagery, whereas forest cover increased by 16%. In this case, debris-flow levees are composed of coarse clastic material dissecting the fan surface in its left part from the apex part to the Alamedin River (downvalley). The main channel has remained invariant, thus keeping a width and depth large enough to transport debris flows across the fan without creating avulsion able to affect the existing forest.

4.2. Regional GLOF-DF frequency for the northern Tien Shan

Overall, we analyzed 401 trees (960 increment cores) sampled on six debris flow fans. In the Ala-Archa Valley, 60 trees were analyzed from AD; 96 trees from AK (see Zaginaev et al., 2016); 77 trees from TE; and 50 trees from TO- In the Alamedin Valley, 52 trees were selected from the SA fan; and 68 trees from KU. In 70% of all cases, samples were from *Picea abies* trees, whereas 20% were from *Juniperus pseudosabina*. The remaining 10% of samples were from *Betula turkestanica*, often growing close to the channel. The oldest living trees in our record dates back to 1783 CE and is located on the TE fan, whereas the youngest tree sampled within this study was from the KU fan; it attained sampling height in 1995.

A total of 764 GDs related to past DF activity were found on the increment cores. In 20% of the cases, GDs were in the form of injuries ($n^{\circ} = 151$). Among the other types of GDs (stem tilting and reaction wood, TRDs, sudden growth decrease), 23% were classified as strong reactions ($n^{\circ} = 175$), whereas 24% were classified as intermediate ($n^{\circ} = 178$) and 33% as weak reactions ($n^{\circ} = 260$). Using this information, we are able to reconstruct 74 GLOF-DF events between 1874 and 2015 on the DF fan. Table 3 shows the GLOF-DF event chronology for each of the catchments. At AD, 9 events were reconstructed, of which three matched with GLOF activity in a side valley of Teztor Valley. These events were recorded in archives and date back to 1953, 1988, and 2012. Average activity for last 100 years at AD was almost 0.08 per year. The largest number of reconstructed events is found on the AK fan (Ala-Archa Valley) where we previously reconstructed 27 events since 1885 CE, thus defining an average frequency (for the last 100 years) of almost 0.26 per year. Nine events were reconstructed at TE from 1900 to 2003 (i.e. 1900, 1946, 1953, 1958, 1961, 1968, 1978, 1980, 2003). Analyses of trees growing on the TO and SA debris fan suggests fairly low process activity when compared with results from the other fans, with only 6 events over the course of the last 100 years (see Table 3). In the case of the KU fan (Alamedin Valley), 17 DF events were reconstructed since 1846, yielding an average frequency (for the last 100 years) of 0.13 events per year. The event dated to 1980 has been detected on the AD, AK, TE and KU fans. Overall, analysis of GLOF-DF variability over the period covered by tree-ring reconstructions suggests the existence of three periods with enhanced activity (Figs. 3 and 4), namely between 1933 and 1943 (10-yr average: 0.45 events yr^{-1}), 1960–1970 (10-yr average: 0.7 events yr^{-1}), and 1995–2005 (10-yr average: 0.45 events yr^{-1}).

4.3. Linkages between moraine-glacier complexes and GLOF-DF activity

Fig. 5A shows the relation between the average GLOF-DF activity reconstructed from tree-ring records at each of the 6 DF fans and their moraine-glacier complexes expressed as the ratio between the area of the moraine complex (M) and the part of the glacier with mostly clean ice (G). We observe that GLOF-DF activity is inversely related to Moraine/Glacier ratio ($r^2 = 0.59$). This means that the modern moraine complexes of the AK and KU catchments are eroded intensively (Fig. 6), adding large amounts of unconsolidated debris to stream channels, thereby contributing to the activation of DF. By contrast, the moraine complexes in the headwaters of the SA and TO fans present less erosive landforms, therefore limiting the amount of material that can be mobilized by DF. The comparison of different catchments shown in Fig. 6 suggests that DF activity in the high mountain valleys is related to a large extent to the process of moraine-glacier complex formation. In those cases where moraine complexes contain limited volumes of unconsolidated debris, DF activity is reduced. In cases where debris cover is largely available (AK and KU), erosion and DF activity is high.

Fig. 5B shows the statistically significant, inversed relationship between average GLOF-DF activity and glacier shrinkage between 1960 and today (G_{2017}/G_{1960}; in%; $\sim r^2 = 0.75$). One can observe that in the AD, AK and KU catchments, glacier did not retreat intensively, and glacier area was reduced by 13–19% since 1960. A somewhat more pronounced retreat of glaciers can be seen in the headwaters of the SA and TO catchments with 24 and 25%, respectively. The most intensive glacier retreat is recorded in the TE catchment with 29%. At the same time, the latter catchment only exhibits a DF activity of 0.1 events per year. By contrast, in those catchments with a smaller reduction of glacier area, GLOF-DF process activity seems to be much higher, as for instance in the case of the AK and KU catchments exhibiting the highest DF activity in Ala-Archa and Alamedin valleys. Consequently, in those catchments where glacier retreat is strongest, meltwater is forced to flow through ample amounts of debris contained in moraine-glacier complexes, which in turn dampens discharge and inhibits the release of DF. Although, the limited number of observation ($n = 6$) prevent to obtain robust conclusions; our results point to the idea that in some regions, the role of moraine complexes in DF activity could be even higher than the role of glacier shrinkage.

5. Discussion

In this study, we have developed a regional GLOF-DF chronology for the northern Tien Shan reaching back to the second half of the 19th century using growth-ring records of trees impacted by past extreme events. Overall, our analyses included 960 increment cores extracted from 430 disturbed trees, allowing identification of 74 GLOF-DF events since 1874 CE. Based on this new GLOF-DF record, we provide first insights into process variability in the northern Tien Shan range, and investigate whether the dissimilar development of moraine complexes during glacier retreat may explain differences in process activity observed on the DF fans.

To overcome the lack of continuous records and to complement historical archives describing DF and GLOF occurrences in the region, we used tree-ring records from trees disturbed by past hydro-geomorphic process activity growing on six characteristic GLOF-DF fans in the Ala-Archa and Alamedin valleys. The idea of complementing historical records was motivated by the fact that archives based on eyewitness records are typically biased in mountain regions due to the remoteness of fans and the rather recent development of settlements and human infrastructures [Mayer et al., 2010; Ballesteros-Cánovas et al., 2017]. Tree-ring records have been considered highly accurate for the dating of extreme hydro-geomorphic events in mountain environments [Stoffel and Corona, 2014; Ballesteros-Cánovas et al., 2016], and to provide information on the sub-annual scale [Stoffel and Bollschweiler, 2008; Bollschweiler et al., 2008]. Hitherto, tree-ring

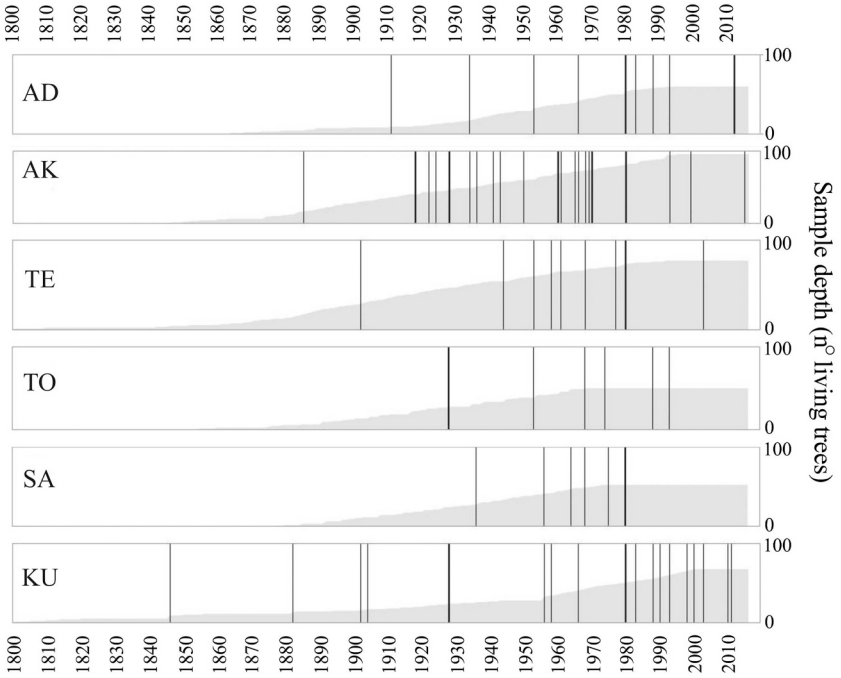

Fig. 3. GLOF-DF chronologies for the six DF catchments. The vertical axis to the right represents the number of trees living during each year of the reconstruction.

approaches have been used successfully to date past events at the catchment scale in Central Asia [Zaginaev et al., 2016; Solomina, Savoskul, & Cherkinsky, 1994; Winchester et al., 2014]. In this study, we were in fact able to reconstruct 59 events that were not known from archival records; but could also confirm the existence of 15 previously known events (Table 3), namely 10 at AK fan, three at AD, and two at TO. Based on this chronology, we showed that process activity varied over time and that GLOF-DF events occurred more frequently during the 1930s, 1960s and 1990s, as compared to other periods. This enhanced activity matches observations from Baimoldaev and Vinohodov (2007) or Medeu (2011), who reported an increase in DF activity in glacierized catchments of Kazakhstan during the 1960s. Besides, this increase in GLOF events during the 1970s to early 1980s in Tien Shan and Pamir has also been corroborated recently by Harrison et al. (2018).

Interestingly, the phase(s) of increased process activity match nicely with the period(s) with close-to-zero reconstructed glacier mass balance of Golubin Glacier in the Ala-Archa catchment since the 1950s and to the early 1970s [Aizen, 1988] and with direct measurements realized at Tuyuksu Glacier in Kazakhstan [Dyurgerov and Mikhalenko, 1995] as well as with the slight glacier advance of Aksay glacier during the 1960s [Bolch, 2015]. A change of glacier mass balance from negative to positive generally leads to an increase in ice flow velocity. As a result of its topography, such a change in flow velocities may indeed have led to blockage of englacial or subglacial channels at the glacier snout of Aksay Glacier, and to subsequent outbursts from englacial water pockets. During periods of negative mass balance, instead, ice flow velocity will decrease, and the lower part of the glacier snout will tend to stagnate, thereby rendering the blockage of englacial channels less likely. Weather anomalies such as prolonged heatwaves or extreme rainfall episodes are referred as possible GLOF-DF triggers [Huggel et al., 2004; Medeu, 2011]. The area studied in this paper is quite small and the distance between individual sites remains within only a few kilometers. Heatwaves will therefore have the same effect across all sites. Stark differences may, by contrast, exist between sites in terms of rainfall intensities and totals as shower cells can be very localized [e.g., Stoffel, Bollschweiler, & Beniston, 2011; Schneuwly-Bollschweiler and Stoffel, 2012]. Their likelihood to occur at any of the study sites does not differ, however. The largest difference is therefore related to geomorphic conditions and controls in the source areas of GLOF-DF processes as these can significantly reduce or amplify the consequences of a heatwave and/or the occurrence of an extreme rainfall [Lugon and Stoffel, 2010].

When looking at differences between the six catchments analyzed, we identify a potential control of GLOF-DF process activity by the typology of the moraine complexes found at the lower end of the glaciers located in their headwaters. To study this phenomenon in detail, we used the ratio of the area of moraine complex (including terminal moraine, rock glacier and debris covered part of glacier) and debris free part of glacier to estimate the degree and intensity of moraine formation processes in the headwaters of the six mountain valleys. This ratio, which reflects moraine formation during the latest stage of glacier degradation in the region, exhibits high inverse correlation with average GLOF-DF activity ($r^2 = 0.59$). At the same time, the reconstructed GLOF-DF activity also inversely depends on the relative decrease in glacier area ($r^2 = 0.75$). This correlations is likely related to the existence of large and thick moraine complexes formed as a result of glacier retreat (Fig. 6), which would then impede efficient drainage of glacial meltwater through intra-moraine channels [Erokhin et al., 2018]. In the valleys where the moraine complex (including debris

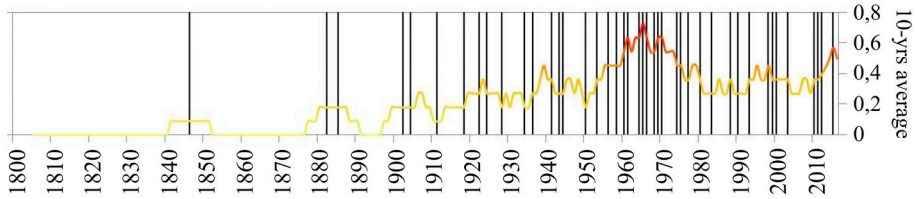

Fig. 4. Composite tree-ring and archival data based GLOF-DF chronology for the Ala-Archa and Alamedin valleys of the Northern Tien Shan and a 10-yr moving average, highlighting periods of enhanced and limited GLOF-DF activity.

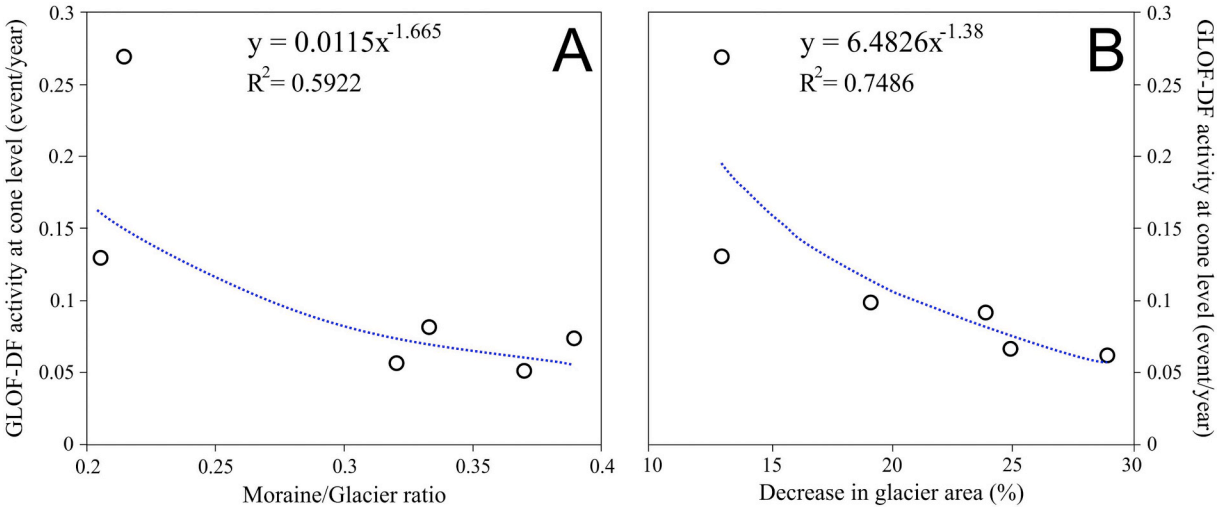

Fig. 5. Relationship between average GLOF-DF activity since 1960 with (A) moraine/glacier ratio and (B) glacier shrinkage.

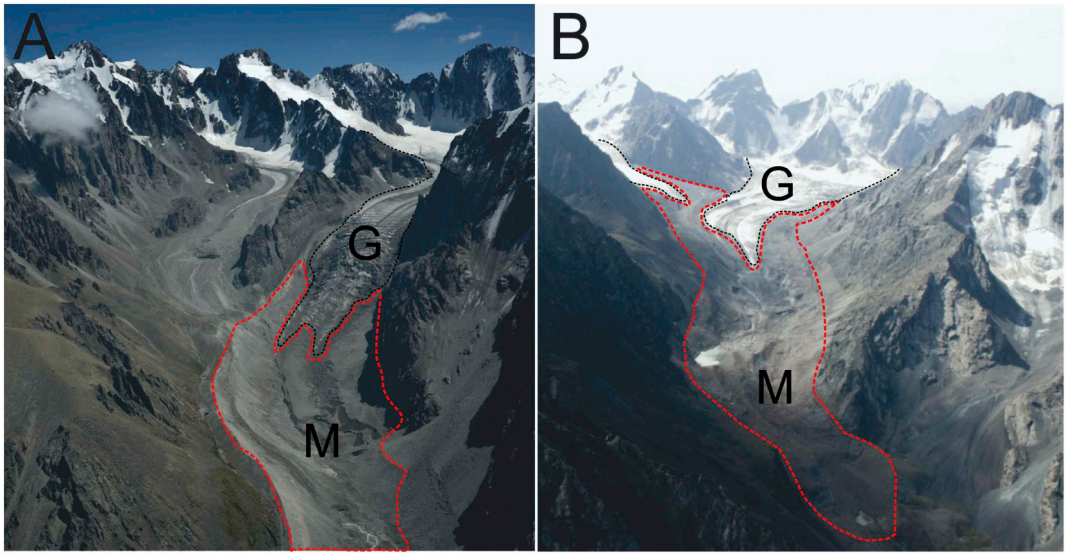

Fig. 6. View of the uppermost parts of the (A) Aksay and (B) Salyk valleys.

covered part of the glacier, terminal moraines and rock glacier) (M) over the open part of the glacier (G), lower GLOF-DF activity is observed. Although the number of observations is too low to draw robust conclusions (with six catchments and 74 GLOF-DF events), results point to a possible role of debris cover and the M-G ratio on hydro-geomorphic process activity.

This means that the lower the M-G ratio (i.e. the smaller the amount of moraine-glacier complex surface), the higher the GLOF-DF activity in the catchment, provided that sediment supply is not a limiting factor [Lugon and Stoffel, 2010]. We explain this relation with two facts: (i) thick moraine complexes (or debris-covered, often stagnant glaciers) are formed as a result of glacial degradation, so these complexes represent superimposed debris lobes creating a single moraine tongue or rock glaciers; (ii) moraine complexes impede and dose the drainage of meltwater from glaciers and limit debris supply, thereby preventing the development of powerful GLOFs and their eventual transformation into DF.

We furthermore realize that GLOF-DF activity is higher in those catchments in which modern moraine complexes were eroded. For instance, in the case of the AK valley (with the highest DF activity and 0.27 events per year according to tree-ring records, or the KU valley where we reconstruct an activity of 0.17), DF are mobilized immediately below the glacier terminus. In these cases, glacier retreat has led to an increase of the debris entrainment zone and additional supply of loose, detrital material to the channel network. In fact, sediment supply at these sites may be even more intensive due to the degradation of permafrost [Marchenko et al., 2007; Huggel et al., 2012]. As a further result of glacier shrinkage and retreat in these valleys, we also observe the formation of new and potentially hazardous lakes (AD, AK). From the 9 events reconstructed on the AD fan, at least three were GLOF events originating from the secondary Teztor Valley. These events, which occurred in 1953, 1988, and 2012 (based on historical evidence), were triggered by glacier meltwater which filled non-stationary lakes [Erokhin et al., 2018]. In the case of the GLOF events at AD, sediment supply can be a limiting factor, such that the last lake outburst in 2018 did not eventually transform into a DF due to limited sediment availability. In the case of the TE catchment, for which a DF activity of 0.09 events per year was obtained, the glacier located in the headwaters of the TE valley is small and does not bear any lake. Here, DF events were released by heavy rainfall episodes.

By contrast, in the case of catchments SA and TO, Holocene terminal moraines have been transformed into rock glaciers, which is a rather typical phenomenon for Northern Tien Shan [Solomina, 2000]. It is possible that in the near future, mean air temperatures permitting, the

moraine of the TE complex might transform into a rock glacier as well. Here, and although the geological conditions, availability of large amounts of detrital material and slope angles in the valley floor might be favorable the formation of DF in catchments SA and TO, the occurrence of GLOF-DF were less frequent here as compared to AD, AK, TE, and KU valleys. The reason for this suppression in process activity at SA and TO is related to the limited capability of glacial meltwater discharge to pass through the rock glacier. Thus, englacial channels limit peak discharge and they do not have enough power to generate high-discharge GLOFs and/or transform into DF. This suggests that DF activity in the mountain valleys addressed in this study will depend considerably on the process of moraine formation and the possibility of moraines being transformed into rock glaciers.

Rock glaciers are limit the flow of meltwater. This process prevents, first of all, the formation of outburst floods, and secondly, greatly limits the supply of detrital material to DF. On the contrary, if a modern moraine complex is eroded by glacier meltwater, the DF processes might be active in the valley, because of the large amount of detrital material that can be eroded as DF propagate downvalley.

6. Conclusions

Tree-ring reconstructions have allowed us to reveal GLOF-DF activity in six different catchments in Northern Tien Shan, namely on the AD, AK, TE, and TO fans (in Ala-Archa) and on the SA and KU fans (in Alamedin). In the valleys where the portion of the moraine complex (M) dominates over the clean part of the glacier (G), we observe lower GLOF-DF activity. The main factor causing high activity is the absence of intense moraine formation, as for instance observed at the AD, AK and KU sites, where meltwaters coming from the glaciers erode modern moraine deposits, supplying loose detrital material to DF as they propagate down the valley. On the contrary, in the valleys of SA and TO, moraine complexes are massive and able to dose runoff coming from the glaciers, thereby preventing erosion of deposits. Any reduction of glaciation effects GLOF-DF activity as well: in the valleys with the largest activity (AD, AK, KU), glacier areas have decreased by 13–15% over the past 60 years, which indicates that glaciers are shrinking more slowly than in the SA and TO valleys, where the area was reduced by 25–26%. At the latter sites, the presence of rock glaciers prevented the occurrence of DF at SA and TO valleys. Thus, moraine complexes are important features when it comes to DF and GLOF activity, and more relevant than glacier shrinkage, at least in the case of northern Tien Shan. Similar situation might be observed in Western and Inner Tian Shan, Hissar-Alai, partially in Pamirs and Hindukush where physical settings are resembling with studied valleys but there are still no data to confirm or deny this hypothesis. Detailed assessments of moraine complexes and their impact on GLOF-DF formation in these regions might contribute to regional mitigation of DF risks. In many other regions worldwide, glacier retreat has led (or will lead) to an increase in DF hazard [Petrov et al., 2017; Stoffel and Huggel, 2012]. In these cases, the exposure of large quantities of unconsolidated, non-vegetated, and sometimes ice-cored glacial sediments caused by glacier retreat [Chiarle et al., 2007] has been identified as the main reason for this increase. During phases of glacier shrinkage, the activity of glacier-related hazards (including GLOF-DF) may increase in heavily glaciated areas, but at some stage their activity is expected to decrease. Our study is thus in line with recent concept of Milner et al. [2017] and with GLOF-DF statistics registered in the Kazakh Tien Shan [Medeu, 2011]. Our research show that in the case of northern Tien Shan, the highest DF activity has been inversely related with glacier area shrinkage, and that the presence of rock glaciers substantially influences DF formation.

Acknowledgment

This study was funded by the Swiss National Science Foundation (SNF, Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung) in the framework of the DEFENCC (n° 152301; Future DEbris Flows and lake outburst floods in Tien Shan: possible impacts of projected Climate Change) project. We also acknowledge the Flood Working Group of PAGES (Past Global Changes) for supporting this special issue on paleoflood records.

References

Aizen, V.B., 1988. Golubin glacier mass balance reconstruction. Data Glaciol. Stud. 62, 119–126.
Aizen, V.B., Kuzmichenok, V.A., Surazakov, A.B., Aizen, E.M., 2006. Glacier changes in the central and northern Tian Shan during the last 140 years based on surface and remote sensing data. Ann. Glaciol. 43, 202–213.
Allen, S., Ballesteros-Cánovas, J., Randhawa, S.S., Singha, A., Huggel, C., Stoffel, M., 2018. Translating the concept of climate risk into an assessment framework to inform adaptation planning: insights from a pilot study of flood risk in Himachal Pradesh, Northern India. Environ. Sci. Pol. 87, 1–10.
Baimoldaev, T., Vinohodov, B., 2007. In: Almaty, Bastau (Ed.), Kazselezaschita: operativnye mery do I posle stikhii, pp. 284 (in Russian).
Ballesteros-Cánovas, J.A., Stoffel, M., Bollschweiler, M., Bodoque del Pozo, J.M., DíezHerrero, A., 2010a. Flash-flood impacts cause changes in wood anatomy of Alnus glutinosa, Fraxinus angustifolia and Quercus pyrenaica. Tree Physiol. 30, 773–781.
Ballesteros-Cánovas, J.A., Stoffel, M., Bodoque del Pozo, J.M., Bollschweiler, M., Hitz, O.M., Diez-Herrero, A., 2010b. Changes in wood anatomy in tree rings of Pinus pinaster Ait. following wounding by flash floods. Tree-Ringr Res. 66, 93–103.
Ballesteros-Cánovas, J.A., Stoffel, M., Spyt, B., Janecka, K., Kaczka, J., Lempa, M., 2016. Paleoflood discharge reconstruction in Tatra Mountain streams. Geomorphology 272, 92–101.
Ballesteros-Cánovas, J.A., Trappmann, D., Shekhar, M., Bhattacharyya, A., Stoffel, M., 2017. Regional flood-frequency reconstruction for Kullu district, Western Indian Himalayas. J. Hydrol. 546, 140–149. https://doi.org/10.1016/j.jhydrol.2016.12.059.
Ballesteros-Cánovas, J.A., Stoffel, M., Benito, G., Rohrer, M., Barriopedro, D., Garcia-Herrera, R., Beniston, M., Bronnimann, S., 2018. On the extraordinary winter flood episode over the North Atlantic Basin in 1936. Ann. N.Y. Acad. Sci. 1–11. https://doi.org/10.1111/nyas.13911.
Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L., Coppola, E., Eckert, N., Huwald, H., 2018. The European mountain cryosphere: a review of its current state, trends, and future challenges. Cryosphere 12 (2), 759–794.
Benn, D., Owen, L., 2002. Himalayan glacial sedimentary environments: a framework for reconstructing and dating the former extent of glaciers in high mountains. Quat. Int. 97–98, 3–25.
Bodoque, J.M., 2015. Challenges in paleoflood hydrology applied to risk analysis in mountainous watersheds – a review. J. Hydrol. 529, 449–467.
Bolch, T., 2015. Glacier area and mass changes since 1964 in the Ala Archa Valley, Kyrgyz Ala-Too, northern Tien Shan. Ice Snow (1), 28–39.
Bollschweiler, M., Stoffel, M., Schneuwly, D.M., Bourqui, K., 2008. Traumatic resin ducts in Larix decidua stems impacted by debris flows. Tree Physiol. 28 (2), 255–263.
Chiarle, M., Iannotti, S., Mortara, G., Deline, P., 2007. Recent debris flow occurrences associated with glaciers in the Alps. Glob. Planet. Chang. 56 (1–2), 123–136.
Dyurgerov, M.B., Mikhalenko, V.N., 1995. Oledeneniye Tien Shanya (Glaciation of Tien Shan). VINITI, Moscow (in Russian).
Engel, Z., Sobr, M., Yerokhin, S.A., 2012. Changes of Petrov glacier and its proglacial lake in the Akshiirak massif, central Tien Shan, since 1977. J. Glaciol. 58 (208), 388–398.
Erochin, S.A., Mamatkanov, D.M., Tuzova, T.V., 2009. Monitoring of Kyrgyz lakes at risk of outburst floods. In: Final Proc. Int. Conf. Floods. Tbilisi, Georgia, pp. 130–147.
Erokhin, S.A., Dikih, A.N., 2003. Risk Assessment of Debris Flow Activities and Flash Floods on the Territory of the Ala - Archa National Park. Bishkek, Izvestiya NAS KR. vol. 15. pp. 130–139 (in Russian).
Erokhin, S., Zaginaev, V., Meleshko, A., Ruiz-Villanueva, V., Petrakov, D., Chernomorets, S., Stoffel, M., 2018. Debris flows triggered from non-stationary glacier lake outbursts: the case of the Teztor Lake complex (Northern Tian Shan, Kyrgyzstan). Landslides 15 (1), 83–98.
Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Mölg, T., Bolch, T., Güntner, A., 2015. Substantial glacier mass loss in the Tien Shan over the past 50 years. Nat. Geosci. 8 (9), 716–722.
Gomez, B., Small, R., 1985. Medial moraines of the haut glacier D'arolla, Valais, Switzerland: debris supply and implications for moraine formation. J. Glaciol. **31** (**109**), **303–307**.
Harrison, S., Kargel, J.S., Huggel, C., Reynolds, J., Shugar, D.H., Betts, R.A., Emmer, A., Glasser, N., Haritashya, U.K., Klimeš, J., Reinhardt, L., Schaub, Y., Wiltshire, A., Regmi, D., Vilímek, V., 2018. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. Cryosphere 12, 1195–1209. https://doi.org/10.5194/tc-12-1195-2018.
Hawkins, E., Sutton, R., 2016. Connecting climate model projections of global temperature change with the real world. Bull. Am. Meteorol. Soc. 97 (6), 963–980.
Hu, Z., Zhang, C., Hu, Q., Tian, H., 2014. Temperature changes in Central Asia from 1979 to 2011 based on multiple datasets. J. Clim. 27 (3), 1143–1167.
Huggel, C., Haeberli, W., Kääb, A., Bieri, D., Richardson, S., 2004. An assessment procedure for glacial hazards in the Swiss Alps. Can. Geotech. J. 41, 1068–1083.
Huggel, C., Clague, J., Korup, O., 2012. Is climate change responsible for changing landslide activity in high mountains? Earth Surf. Process. Landf. 37 (1), 77–91.
Jansky, B., Sobr, M., Engel, Z., 2010. Outburst flood hazard: case studies from the Tien-

Shan mountains, Kyrgyzstan. Limnol. Ecol. Manag. Inland Waters 40, 358–364.
Kogelnig-Mayer, B., Stoffel, M., Schneuwly-Bollschweiler, M., Hübl, J., Rudolf-Miklau, F., 2011. Possibilities and limitations of dendrogeomorphic time-series reconstructions on sites influenced by debris flows and frequent snow avalanche activity. Arct. Antarct. Alp. Res. 43 (4), 649–658.
Lopez-Saez, J., Corona, C., Stoffel, M., Astrade, L., Berger, F., Malet, J.P., 2012. Dendrogeomorphic reconstruction of past landslide reactivation with seasonal precision: the Bois Noir landslide, southeast French Alps. Landslides 9 (2), 189–203.
Lugon, R., Stoffel, M., 2010. Rock-glacier dynamics and magnitude–frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps. Glob. Planet. Chang. 73 (3–4), 202–210.
Marchenko, S., Gorbunov, A., Romanovsky, V., 2007. Permafrost warming in the Tien Shan Mountains, Central Asia. Glob. Planet. Chang. 56, 311–327. https://doi.org/10.1016/j.gloplacha.2006.07.023.
Mayer, B., Stoffel, M., Bollschweiler, M., Hübl, J., Rudolf-Miklau, F., 2010. Frequency and spread of debris floods on fans: a dendrogeomorphic case study from a dolomite catchment in the Austrian Alps. Geomorphology 118 (1–2), 199–206.
Medeu, A.R., 2011. Debris Flows in South-Eastern Kazakhstan: Fundamentals of Management (Almaty).
Meleshko, A., Konovalov, Yu, Zaginaev, V., Anatskaya, E., 2017. Remote Sensing Based Monitoring: Glacier Changes in Ala-Archa and Alamedin River Basins in the Northern Tien-Shan. RUDN, Moscow, pp. 138–142.
Melton, M.A., 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. J. Geol. 73, 1–38.
Milner, A.M., Khamis, K., Battin, T.J., Brittain, J.E., Barrand, N.E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G.M., Jacobsen, D., Hannah, D.M., 2017. Glacier shrinkage driving global changes in downstream systems. Proc. Natl. Acad. Sci. U. S. A. 114, 9770–9778.
Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Meehl, G.A., 2010. The next generation of scenarios for climate change research and assessment. Nature 463 (7282), 747.
Narama, C., Duishonakunov, M., Kääb, A., 2010. The 24 July 2008 outburst flood at the western Zyndan glacier lake and recent regional changes in glacier lakes of the Teskey Ala-Too range, Tien Shan, Kyrgyzstan. Nat. Hazards Earth Syst. Sci. 10, 647–659.
Narama, C., Daiyrov, M., Duishonakunov, M., Tadono, T., Sato, H., Kääb, A., Abdrakhmatov, K., 2018. Large drainages from short-lived glacial lakes in the Teskey Range, Tien Shan Mountains, Central Asia. Nat. Hazards Earth Syst. Sci. 14 (4), 983–995. https://doi.org/10.5194/nhess-18-983-2018.
Petrakov, D., Shpuntova, A., Aleinikov, A., Kääb, A., Kutuzov, S., Lavrentiev, I., Stoffel, M., Tutubalina, O., Usubaliev, R., 2016. Accelerated glacier shrinkage in the Ak-Shyirak massif, Inner Tien Shan, during 2003–2013. Sci. Total Environ. 562, 364–378.
Petrov, M.A., Sabitov, T.Y., Tomashevskaya, I.G., Glazirin, G.E., Chernomorets, S.S., Savernyuk, E.A., Tutubalina, O.V., Petrakov, D.A., Sokolov, L.S., Dokukin, M.D., Mountrakis, G., Ruiz-Villanueva, V., Stoffel, M., 2017. Glacial lake inventory and lake outburst potential in Uzbekistan. Sci. Total Environ. 592, 228–242.
Raup, B., Racoviteanu, A., Khals, S.J.S., Helm, C., Armstrong, R., Arnaud, Y., 2007. The GLIMS - geospatial glacier database: a new tool for studying glacier change. Glob. Planet. Chang. 56, 101–110. https://doi.org/10.1016/j.gloplacha.2006.07.018.
Rinntech, 2011. LINTAB Präzision - Jahrring für Jahrring. http://www.rinntech.com/content/view/16/47/lang.
Schneuwly, M., Corona, C., Stoffel, M., 2013. How to improve dating quality and reduce noise in tree-ring based debris-flow reconstructions. Quat. Geochronol. 18, 110–118.
Schneuwly-Bollschweiler, M., Stoffel, M., 2012. Hydrometeorological triggers of periglacial debris flows in the Zermatt Valley (Switzerland) since 1864. J. Geophys. Res. Earth Surf. 117, F02033.
Solomina, O., 2000. Retreat of mountain glaciers of northern Eurasia since the Little Ice Age maximum. Ann. Glaciol. 31, 26–29.
Solomina, O., Savoskul, O., Cherkinsky, A., 1994. Glacier variations, mudflow activity and landscape development in the Aksay Valley (Tian Shan) during the late Holocene. The Holocene 4 (1), 25–31.
Sorg, A., Bolch, T., Stoffel, M., Solomina, O., Beniston, M., 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nat. Clim. Chang. 2, 725–731.
Sorg, A., Huss, M., Rohrer, M., Stoffel, M., 2014. The days of plenty might soon be over in glacierized Central Asian catchments. Environ. Res. Lett. 9, 104018. https://doi.org/10.1088/1748-9326/9/10/104018.
Stoffel, M., 2008. Dating past geomorphic processes with tangential rows of traumatic resin ducts. Dendrochronologia 26 (1), 53–60.
Stoffel, M., 2010. Magnitude–frequency relationships of debris flows - a case study based on field surveys and tree-ring records. Geomorphology 116 (1–2), 67–76.
Stoffel, M., Bollschweiler, M., 2008. Tree-ring analysis in natural hazards research – an overview. Nat. Hazards Earth Syst. Sci. 8, 187–202.
Stoffel, M., Corona, C., 2014. Dendroecological dating of geomorphic disturbance in tress. Tree Ring Res. 70, 3–20.
Stoffel, M., Hitz, O.M., 2008. Rockfall and snow avalanche impacts leave different anatomical signatures in tree rings of juvenile Larix decidua. Tree Physiol. 28 (8), 1713–1720.
Stoffel, M., Huggel, C., 2012. Effects of climate change on mass movements in mountain environments. Prog. Phys. Geogr. 36 (3), 421–439.
Stoffel, M., Bollschweiler, M., Beniston, M., 2011. Rainfall characteristics for periglacial debris flows in the Swiss Alps: past incidences–potential future evolutions. Climatic Change 105 (1–2), 263–280.
Stoffel, M., Casteller, A., Luckman, B.H., Villalba, R., 2012. Spatiotemporal analysis of channel wall erosion in ephemeral torrents using tree roots—an example from the Patagonian Andes. Geology 40 (3), 247–250.
Stoffel, M., Tiranti, D., Huggel, C., 2014. Climate change impacts on mass movements - case studies from the European Alps. Sci. Total Environ. 493, 1255–1266.
Usubaliev, R., Erokhin, S., 2007. Formation of High-mountainous Lakes as a Consequence of the Degradation of the Modern Glaciation of the Tien Shan. Moscow, Data of Glaciological Studies 3. pp. 134–137.
Vinogradov, Yu., 1980. Sketches of Mudflows. Leningrad. Gidrometeoizdat, pp. 144.
Wang, W., Xiang, Y., Gao, Y., Lu, A., Yao, T., 2015. Rapid expansion of glacial lakes caused by climate and glacier retreat in the Central Himalayas. Hydrol. Process. 29 (6), 859–874.
Winchester, V., Passmore, D., Harrison, S., Rae, A., Severskiy, I., Pimankina, N., 2014. Dendrogeomorphological and Sedimentological Analysis of Debris Flow Hazards in the Northern Zailiiskiy Alatau, Tien Shan Mountains, Kazakhstan. Vulner. Land Syst. Asia 91–113.
Wu, J., 1992. Characteristics of erosion and deposition from debris flows. In: Proceedings of the Chengbu Symposium. Erosion, Debris Flow and Environment in Mountain Regions. IAHS Publ. no. 209, pp. 355–359.
Zaginaev, V., 2013. The Teztor Lake Outburst Event (Northern Tien-Shan). Monitoring, Forecasting of Hazardous Processes and Phenomena in the Territory of the Kyrgyz Republic. vol. 10. MES of KR, pp. 563–570.
Zaginaev, V., Erokhin, S., Ballesteros-Cánovas, J.A., Matov, E., Stoffel, M., 2016. Reconstruction of glacial lake outburst floods in northern Tien-Shan: implications for hazard assessment. Geomorphology 269, 75–84.